EFFICIENCY TEST AND HEAT BALANCE OF A 1-3 HORSE POWER OTTO GAS ENGINE

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TOWNE
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4 June '98. Sen. C. E. Univ.

Test of an Otto Gas Engine.

This test consists of a measurement of the indicated horse-power, the brake horse-power and the distribution of heat in the engine.

The engine is a part of the equipment of the Mechanical Laboratory of the University of Pennsylvania, and was built at the Otto Gas Engine Works, Philadelphia. It has a vertical cylinder with a trunk piston connected to a cranked shaft which carries a fly-wheel on one end, and a gear wheel on the other. Into the latter there feeds a larger wheel having

twice the number of teeth and on its shaft an eccentric which, by means of an eccentric rod actuates the exhaust as well as the gas admission valve. The admission of gas is controlled by a governor. To the end of the eccentric rod is attached a lever on one end of which is a weight while on the other there is a spiral spring Projecting downward from the fulcrum is a rod cast in one piece and at right angles with the lever carrying a hook at its lower end. When the rod is

The Governor.

vertical the hook engages with a projection on the valve stem and therefore lift the valve when the fulcrum moves upward unless the motion

of the fulcrum is so rapid that the inertia of the weight overcomes the pull of the spring and releases the valve stem. In such a case no gas is admitted, no explosion takes place so that the speed of the engine is reduced. The speed of the engine may be changed by altering the position of the weight on the lever.

The mixture of gas and air after being taken into the cylinder is compressed into a narrow tube placed inside a cast iron cylinder which is lined with asbestos. The flame from a burner plays around the tube and keeps it hot enough to ignite the mixture.

The air used by the engine passes through a pipe which communicates with a space between the bottom wall of the cylinder and the base of the engine. It is admitted into the cylinder by a valve lifted by suction which may be called the gas admission valve. This valve also regulates the mixture of gas and air. The seat of the valve has small holes in it which communicate with the gas main through the gas admission valve already mentioned; the space under the valve communicates with the air. When the valve is lifted a mixture of air and gas is taken in the composition of

which is determined by the relative area of the holes in the seat to the area under the valve. This gives a considerable preponderance to the amount of air.

The cycle of this engine belongs to the class which ignite at constant volume with previous compression. On an upward stroke a mixture of air and gas is drawn into the cylinder. When the piston starts on its downward stroke the air admission valve, which is opened by suction, is closed and the mixture of air and gas compressed until the end of that stroke when explosion occurs. Expansion occurs dur-

ing the next stroke which is for-
ward and on the fourth stroke
the burned gases are expelled.
This completes the cycle of
changes in the engine. Thus
each stage of the repeats itself
every four strokes. To make
this possible the eccentric makes
only one half as many revolu-
tions as the crank and con-
sequently only opens the exhaust
and gas admission valves once
every four strokes.

Since the temperature of the
gases in the cylinder after
ignition is very high it is
necessary to have some
means of maintaining the
temperature of the cylinder
walls below that temperature.

This result is obtained by permitting a constant flow of water through a jacket surrounding the cylinder.

To have the engine run properly several precautions are necessary. All the valves must be cleaned and fit their seats so as to prevent any leakage. If the compression is not good the charge will not explode.

The ignition tube must be kept hot at the lower end otherwise the explosions will be late and the engine will not develop power.

A great deal also depends

on the mixture of gas and air. This is regulated by the motion of the gas admission valve, which should be about $\frac{3}{32}$ of an inch.

Instruments.

The gas used in the cylinder and for ignition was measured by separate meters placed in pipes leading from the gas main to the cylinder used.

ignition tube respectively.
Between the meter measuring
the gas used in the cylinder
and the engine was placed
a bag to act as a reservoir
and prevent sudden calls
upon the capacity of the
meter. The air was meas-
ured by a meter, the air
being supplied under pressure
from a blower through the
meter to a bag placed between
the meter and the engine.
The temperatures were taken with
Fahrenheit thermometers.
A counter connected to the
eccentric gave the number of
revolutions when its readings
were multiplied by two.
Explosions were taken with a

counter attached to the valve stem of the gas admission valve.

The brake consisted of a rope hung on the fly-wheel and held by wooden guides. On one side it carried a scale pan while on the other side a spring balance was hung in an inverted position the lower end being fixed on the floor

Cards were taken with a Thompson Indicator the string being attached to a rod projecting eccentrically from the fly-wheel.

Analyses of the exhaust gases were made with an Elliott Apparatus during the test. The Hempel Apparatus

was used in analyzing the fuel gas. The water flowing through the cylinder jacket was caught in buckets and weighed.

Methods of Measurement.

The engine was run under the conditions under which it was to be tested for about one half hour before starting the test in order to make the various readings constant. The test was started by a simultaneous reading of the time, the explosion counter and the revolution counter. The jacket water was then turned on and allowed to flow at the same rate as before starting the test; it having been turned off momentarily at the start. Readings of the temperature of the air, cylinder gas, exhaust gases, and jacket water were taken;

also the pressure of the air and gas; the readings of the counters; the pull on the brake rope, and the rates of the three meters. These readings were taken at regular intervals and the time noted.

Each time a bucket was filled with jacket water it was weighed and the time noted.

During the test a number of indicator cards were taken and two samples of exhaust gasses analized.

The test was concluded by turning off the jacket water just previous to a simultaneous reading of the time, the explosion counter and the revolution counter.

After the test the clearance vol-

ume was found. A bucket was filled with water and weighed, the piston was removed and water poured in the cylinder until it reached a measured distance from the top; the remaining water and bucket was weighed and from these weights the clearance volume was readily determined.

The three meters were calibrated by connecting them up in series with a stand pipe filled with water; the water was run out and weighed and the readings of the meters were corrected by obtaining the volume of air which passed through the meter from the weight of water.

Readings.

Table 1.

Time.	Counters.	
	Revolution.	Explosion.
3.30	3990	5933
3.38	4888	7091
3.50	7346	8908
4.00	9530	10718
4.08	11016	12084
4.15	12644	13361
4.21	14012	14472
4.32	16461	16544
4.39	17925	17778
5.00	22340	21574

Table 2.

Temperatures.

Time.	Gas. Inlet.	Gas. Exhaust	Air.	Jacket Water. Inlet.	Jacket Water. Outlet.
3.35	72	460	69	80	164
3.47	72	458	69	68	136
3.52	72	478	69	68	130
4.02	73	490	69	66	136
4.13	73	484	68	68	176
4.20	74	488	69	66	160
4.27	74	506	68	66	152
4.37	74	500	68	66	170

Table 3.

Jacket Water.

Time.	No. Bucket	Weight. lb.	Weight. oz.
3.42	1	18.0	.25
3.50	2	16.5	7.75
3.59	1	20.5	4.00
4.06	2	18.0	4.00
4.25	1	18.5	6.00
4.32	2	16.5	3.125
4.39	1	16.5	4.75
4.52	2	22.5	7.00
5.00	1	15.5	6.50

Bucket No. 1. — 2.5 lb. 3.25 oz.

Bucket No. 2. — 2.0 lb. 5.5 oz.

Table 4.

Meters.

Air.			Cylinder Gas. Ignition.					
Time.	Ft.	Rate Sec.	Time.		Ft.	Time.		Ft.
3.32	1	24	3.33 1/20	3.34 13/20	.5	4.16	4.43 3/5	3
3.44	1	24	3.44 38/60	3.45 3/4	.5	4.43 3/5	4.53 1/5	1
3.54	1	24	3.55	3.56	.5			
4.02	1	24	4.04	4.05	.5			
4.11	1	24	4.12 3/10	4.13 1/2	.5			
4.18	1	24 3/5	4.18	4.19	.5			
4.27	1	24 3/5	4.29 1/5	4.30 1/5	.5			
4.36	1	24 4/5	4.35	4.36 1/2	.5			
			4.13 1/2	4.18	2.			
			4.18	4.24 4/5	3.			
			4.24 4/5	4.29 1/5	2.			
			4.36	4.41	2.			

Additional Readings.

Pressure of air in main = 4.8" of water

Pressure of gas in main = 4.2" of water

Pull on brake rope (spring balance) = 5.875 lb.

Pull on brake rope (scale pan) = 1.516 lb.

Calibration of Meters.

Air meter ---- 1 cu ft. = 1 cu. ft.

Cylinder meter -- 1 cu. ft. = .965 cu ft.

Ignition meter 1 cu. ft. = 1 cu ft.

H_b = barometric height (inches of mercury.)

P_b = barometric pressure.

= $.4908 \times H_b \times 144$.

H_a = height of gauge on air main inches of water.

P_a = pressure corresponding to $H_a = 62.5 \times \frac{H_a}{12}$.

P_{av} = vapor pressure in air main assuming the air saturated at the temperature t_a of air in the main.

γ_{av} = weight of moisture in one cu. ft. of air when saturated at temperature t_a.

T_a = absolute temperature of air.

H_g = height of gauge in gas main (inches of water)

P_g = pressure corresponding to $Hg = \frac{62.5}{12} Hg$.

P_{gv} = pressure in gas main assuming the gas half saturated. This pressure was obtained by taking one half the pressure corresponding to the temperature t_g of gas in main.

T_g = absolute temperature of gas

T_{gv} = absolute temperature of saturation corresponding to P_{gv}.

γ_{gv} = weight of moisture in one cu. ft. when saturated at pressure P_{gv}.

w_{gv} = weight of moisture in one cu. ft. of gas. $= \frac{T_{gv}}{T_g} \gamma_{gv}$.

R_a, R_g, R_e = constants for air, gas and exhaust gases.

T_e = absolute temperature of exhaust gases.

t_e = temperature Fahrenheit of exhaust gases.

V_g = volume of gas per minute without ignition.

V'_g = volume of gas per minute for ignition.

N = number of revolutions of fly-wheel per minute.

N_e = number of explosions per minute.

N_i = possible number of explosions per minute. = $\frac{1}{2}$ N.

V_a = total volume of air per minute.

V'_a = volume of air per minute for explosions.

$$V_a' = V_a - \frac{N_e' - N_e}{N_e'}(V_g + V_a)$$

L_s = length of stroke in feet.

a = area of piston.

M_j = weight of jacket water per minute.

t_1 = temperature of water entering jacket.

t_2 = temperature of water leaving jacket.

q = heat of liquid.

ρ = internal heat of vaporization.

c_v = specific heat, at constant volume, of superheated vapor.

H = weight of hydrogen in gas for explosions per minute.

See properties of gases.

W_{ev} total weight per minute of moisture in exhaust gases.

$W_{ev} = \gamma_{ta} V_a + w_{gv} V_g + 9H.$

w_{ev} = weight of moisture per cu. ft. of exhaust gases.

V_e = volume of exhaust gases per minute.

a_e = area of exhaust pipe.

M_e = weight of exhaust gases per minute.

$$M_e = M_a + M_g + \gamma_{ta} V_a + w_{ga} V_g.$$

Indicated Horse Power.

p_{mw} = mean effective pressure during stroke.

$$I.H.P = \frac{p_{mw} \bar{T}_1 a N_2}{33000}.$$

Brake Horse Power.

W_1 = weight in scale pan plus the weight of pan. (lbs.)

W_2 = pull of spring balance corrected for zero reading.

d = dia. of fly-wheel.

$$B.H.P = \frac{\pi d N (W_2 - W_1)}{33000}.$$

Gas.

M_g = weight of gas per minute without ignition.

$$M_g = \frac{(P_e + P_g - P_{gv}) Va}{Ra\, Ta}$$

m_g = weight of gas per explosion

$$m_g = \frac{M_g}{N_e}$$

h = heat of combustion of gas per minute.

$h = M_g \times 13650$ (See properties of gases)

h' = heat of combustion of gas per explosion.

$$h' = \frac{h}{N_e}$$

Air.

M_a = total weight of air per minute.

$$M_a = \frac{(P_e + P_a - P_{av})\ V_a}{R_a T_a}$$

M_a' = weight of air per minute for explosions.

$$M_a' = M_a \frac{V_a'}{V_a}$$

m_a = weight of air per explosion

$$m_a = \frac{Ma'}{Ne}$$

Heat Balance.

This balance was made by considering the average amount of heat entering and leaving the engine per minute; hence all values are in B. T. U. units. They are reckoned from 32° Fahrenheit.

Heat Entering Engine.

Heat in air.

a. Internal heat of air.

$$\frac{(P_b + P_a - P_{av})\, V_a}{.41 \times 778} \left[1 - \frac{495}{T_a}\right]$$

b. Internal heat of vapor.

$$\gamma_a V_a (q_{ta} + p_{ra})$$

Heat in gas.

a. Internal heat of gas.

$$\frac{(P_b + P_g - P_{gv})\, V_g}{.41 \times 778} \left[1 - \frac{493}{T_g}\right]$$

b. Internal heat of vapour.

$$w_{gv}\, V_g \left[q_{vg} + p_{vg} + .369 (T_g - T_{vg})\right.$$

Work done on air.

$$\frac{(P_b + P_a)\, V_g}{778}$$

Work done on gas.

$$\frac{(P_b + P_g)\, V_g}{778}$$

Heat of combination of gas.

$M_g \times h$.

Heat obtained from engine.

Indicated work $= \frac{I.H.P. \times 33000}{778}$.

Jacket water $= M_g (q_{t_2} - q_{t_1})$

Heat in exhaust gases.

γ = weight of moisture per cu. ft. in exhaust gases, reduced to temperature t of saturation.

w_e = weight of moisture per cu. ft. of exhaust gases. = $\frac{W_e}{V_e}$

V_e = volume of exhaust gases per minute.

W_e and V_e were determined by approximation from the formula.

$$V_e = \frac{(M_e - W_{ev}) R_e T_e}{(P_e - P_{ev})} \text{ and } \gamma T = w_e T_e.$$

P_{ev} corresponds to t.

v_e = velocity of gases in the exhaust pipe. = $\frac{V_e}{a_e}$.

a. Energy of velocity of gases.

$$\frac{M_e v_e^2}{2g \times 778}$$

b. Energy in gases.

$$\frac{(M_e - W_{ev})\,R}{778 \times .41}\,(T_e - 493)$$

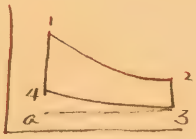
c. Energy of moisture in exhaust gases.

$$W_{ev}\left[q_t + p_t + .369\,(T_e - T)\right]$$

d. Work done expelling exhaust gases.

$$\frac{P_b \times a \times L \times N}{778 \times 144 \times 2}$$

Type Efficiency.



The cycle of this engine consists of six operations as already outlined:-

1. Taking in a charge of air and gas. (a-3).
2. Compressing the charge. (3-4).
3. Ignition of the charge. (4-1).
4. Expanding the heat gases. (1-2).
5. Expelling the burned gases (2-3-a)

To carry out this process perfectly the gases should neither take heat nor give heat to the cylinder walls, hence the lines (3-4) and (1-2) should be adiabatics, and the lines (4-1) and (2-3) should be constant volume lines in the perfect cycle. It is needless to say these conditions are never

realized in an actual engine.
The heat added in the cycle is $c_v (T_1 - T_4)$ and that taken away is $c_v (T_2 - T_3)$. The type efficiency E' is then =

$$\frac{(T_1 - T_4) - (T_2 - T_3)}{T_1 - T_4} = 1 - \frac{(T_2 - T_3)}{(T_1 - T_4)}$$

now $\frac{T_1}{T_4} = \frac{T_2}{T_3}$ or $\frac{T_1 - T_4}{T_4} = \frac{T_2 - T_3}{T_3}$

hence $E' = 1 - \frac{T_3}{T_4}$

and $\frac{T_3}{T_4} = \left(\frac{v_3}{v_4}\right)^{k-1}$ where $k = 1.41$

hence $E' = 1 - \left(\frac{v_3}{v_4}\right)^{k-1}$

Actual Efficiency.

This is found by dividing the heat of combustion of the gases used per minute by the heat equivalent of the work per minute.

Analysis and Properties of Gases.

Philadelphia illuminating gas.

	Per cent Volume	w = Weight in One lb. of gas.
CH_4	26.6	.3155
C_2H_4	4.2	.0871
H_2	40.6	.0613
CO	18.5	.3840
O_2	.43	.0051
CO_2	2.10	.0685
N_2	7.57	.0785

	Heat of Combination of One Lb.
CH_4	23200
C_2H_4	21200
H_2	52500
CO	4300

Heat of Combination in One Lb. of Gas.

CH_4	7310
C_2H_4	1845
H_2	3160
CO	1650

Total heat of combustion of one pound of gas = 13650

	C_p	C_v	$w(C_p - C_v)$
CH_4	.593	.470	.000316
C_2H_4	.404	.332	.00308
H_2	3.409	2.406	.0055
CO	.245	.173	.0276
O_2	.217	.155	.0605
CO_2	.216	.171	.00627
N_2	.243	.171	.0388
			.14206

$R_g = 778 \times .142 = 110.5$

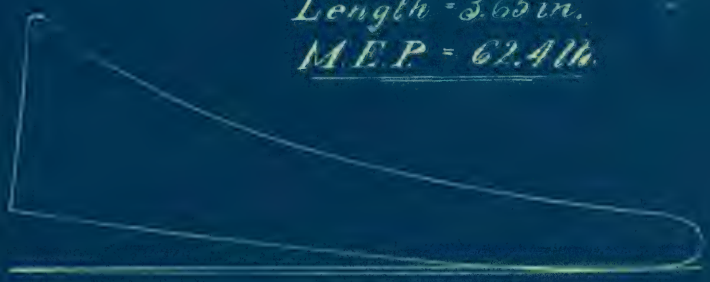
Exhaust Gases.

	Percent Volume	w_1 = Weight in One Lb. of ga
CO_2	10.4	.165
O_2	5.5	.058
CO	.35	.003
N_2	83.75	.774

	$w_1 (c_p - c_v)$
CO_2	.00741
O_2	.00359
CO	.00022
N_2	.05418
	.06540

$R_e = 778 \times .0654 = 50.9$

Area = 1.46 sq. in.
Length = 3.65 in.
M.E.P. = 62.4 lb.



Mean Card.

Scale - 120 = 1"

Calibration Curve.

The Mean Card given on the preceding page was used for the determination of the I. H. P. of the engine. On each of the several cards taken from the engine ordinates were erected at equal distances along the length of the card. Taking any particular ordinate it was measured on each card and the mean of all the measurements of that particular ordinate taken as an ordinate for the mean card. It was, however, corrected for the spring error by the use of the calibration curves given.

General Data and Results.

1. Date of test.	May 6, 1898.
2. Duration of test.	90 min.

Dimensions.

3. Diameter of cylinder.	3 ins.
4. Area of piston.	7.06 sq. ins.
5. Length of stroke	.417 ft.
6. Circumference of fly-wheel	6.28 ft.

Pressures.

7. Atmospheric pressure (barometer)	29.8 ins.
8. Pressure in air main. (inches of water.)	4.8 ins.
9. Pressure in gas main. (inches of water.)	4.2 ins.
10. Maximum pressure in cylinder above atmosphere	162 lb.

11.	Mean effective pressure during stroke when an explosion occurs.	62.4

Temperatures.

12.	Of air.	69° Fah.
13.	Of gas.	73° Fah.
14.	Of exhaust.	483° Fah.
15	Of water entering jacket.	68.5° Fah.
16.	Of water leaving jacket.	151.8° Fah.

Horse-Power.

17.	Number of revolutions per minute.	430
18.	Load on brake.	4.359 lb.
19.	Brake horse-power	.356
20.	Number of explosions per minute.	173.8
21.	Indicated horse-power.	.965

Gas.

22. Gas used per hour without ignition. 26.58 cu. ft.
23. Gas used per hour for ignition. 6.34 cu. ft.
24. Total gas per hour. 32.92 cu ft.
25. Volume of gas per explosion. .000254 cu. ft.
26. Weight of gas per explosion. .0000904 lbs.
27. Heat of combination of gas per pound. 13965 B.T.U.
28. Heat of combination of gas per explosion. 1.263 B.T.U.
29. Gas used per I.H.P. per hour without ignition 27.5 cu-ft.
30. Gas used per I.H.P. per hour with ignition. 34.05 cu-ft
31. Gas used per B.H.P per hour without ignition. 74.8 cu-ft.

32. Gas used per B.H.P. per hour with ignition 92.5 cu.ft.

Air.

33. Air used per hour 148.8 cu.ft.

34. Air used per hour for explosions. 110.0 cu.ft.

35. Air used per explosion. (Volume.) .01105 cu.ft.

36. Air used per explosion. (weight) .000811 lbs.

37. Ratio of volume of air per explosion to volume of gas per explosion. 4.35

38. Ratio of weight of air per explosion to weight of gas per explosion. 8.98

Efficiencies.

39. Type efficiency .353

40.	Actual efficiency	.187
41.	Ratio of actual efficiency to type efficiency	.530
42.	Mechanical efficiency	.368

Heat Balance.

This balance is expressed in terms of one hundred heat units entering the engine.

Heat Entering	Per Minute	In 100 B. T. U.
In air	1.125	.48
In moisture of air	2.83	1.22
In gas	.224	.096
In moisture of gas	.284	.122
Work done on air	6.76	2.91
Work done on gas	1.208	.52
Heat of Combustion	220.	94.7

Heat Leaving

	Per minute	In 100 B.T.U.
Indicated Work	41.0	17.65
Velocity of gases	.002	.00
In exhaust gases	12.7	5.47
Moisture in exhaust gases	31.3	13.5
Work of expulsion of gases	11.88	5.12
Jacket	132.75	57.2
Radiation	2.78	1.2

The radiation is calculated from the difference between the rest of the energy obtained from the engine and the total heat given to the engine

3 1198 03073 4045
N/1198/03073/4045X